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Zonally Robust Decentralized Optimization for Global Energy Interconnection: Case Study on Northeast Asian Countries

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***Abstract*— Nowadays, the entire world is facing challenges in energy and environment. To resolve these problems, the power systems are interconnected to promote the development of renewable energy sources (RESs). However, the economic dispatch (ED) problem for the global energy interconnection (GEI) should tackle two issues: 1) handle the uncertainty from RES and allocate the responsibility among the interconnected countries and 2) protect the information privacy through the dispatch. Motivated by the above, this article proposes a zonally adjustable robust decentralized ED model for the GEI. In the model, each country is only responsible for its own uncertainty, and tie-line power flows remain unchanged under uncertainties. Moreover, an alternating direction method of multipliers (ADMM)-based fully distributed algorithm is used, in which only limited information should be exchanged between neighboring countries. Finally, a case study on the Northeast Asian countries verifies the effectiveness of the proposed method.**

***Note to Practitioners*—Since the renewable energy generation has a spatial correlation among regional countries, global energy interconnection (GEI) aims to combine several power systems together to promote the renewable energy accommodation. However, two problems need to be considered: 1) *Information Privacy:* The information privacy of the power system in each country should be preserved, which prevents the GEI from conducting a centralized optimal dispatch framework and 2) *Uncertainty:* The uncertain output of renewable energy resources brings challenge to the power system secure operation. The main contribution of this article is to set up a zonally robust decentralized optimization for the GEI, where the zonally robust economic dispatch (ED) is conducted by the area control error (ACE) system to manage the difference between scheduled and actual generation under the uncertainties, and the alternating direction method of multipliers (ADMMs) algorithm is adopted for decentralizing the zonally adjustable robust ED model, which only needs limited information. In particular, this article uses a real-world example from Northeast Asian Countries to help engineers understand the advantages of the GEI and the new dispatch framework.**

***Index Terms*— Decentralized algorithm, economic dispatch (ED), global energy interconnection (GEI), zonal robustness.**

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NOMENCLATURE

Sets and Indices

t	Index of time periods.
i, j, d, m, n	Index of buses.
l	Index of transmission lines.
ω, φ	Index of countries.
$\mathbf{T}$	Set of time periods.
$\mathbf{\Pi}$	Set of buses.
$\mathbf{\Pi}_G$	Set of unit buses.
$\mathbf{\Pi}_H$	Set of hydropower buses.
$\mathbf{\Pi}_R$	Set of RES buses.
$\mathbf{\Pi}_D$	Set of load buses.
$\mathbf{L}_{in}$	Set of country-internal lines.
$\mathbf{L}_{tl}$	Set of tie-lines.
$\mathbf{\Omega}$	Set of countries.
$\mathbf{\Lambda}$	Set of adjacent country pairs.

Variables

Cost	Total operation cost.
$F_l(t)$	Power flow of country-internal line l at time t.
$G_i(t)$	Output of unit i at time t.
$R_j(t)$	Output of RES j at time t.
$R_j^c(t)$	Curtailment limit of RES j at time t.
$\Delta R_j(t)$	Uncertainty level of RES j at time t.
$T_l(t)$	Power flow of tie-line l at time t.
$T_{mn}(t)$	Power flow of tie-line with start bus m and end bus n at time t.
α_{ij}	Participation factor of unit i for RES j.
θ_i	Voltage angle of bus i.
θ_{ref}	Reference voltage angle.

Parameters

a_i, b_i	Operation cost coefficients of unit i.
B	Bus admittance matrix.

$C_{G(R,D,T)}$	Permutation matrix of units, RESs, loads, and tie-lines according to bus indices.
$D_d(t)$	Load demand of bus d at time t (with power loss).
E_l	Contracted transactive energy on tie-line T_l during studied horizons.
$\bar{F}_l$	Maximum capacities of country-internal line l.
G_i, $\bar{G}_i$	Minimum and maximum capacities of unit i.
$\underline{\Delta G}_i$, $\overline{\Delta G_i}$	Minimum and maximum ramping rates of unit i.
$H_{l,i}$	Sensitivity factor of bus i to transmission line l.
p_R	Penalty coefficient of RES's curtailment.
$R_j^f(t)$	Forecasted output of RES j at time t.
$\bar{T}_l$	Maximum capacities of tie-line l.
W_i	Maximum output energy of hydropower unit i during studied horizons.
x_{mn}	Reactance of the tie-line mn.

Functions and Definitions

$\cdot^0$	Base point value of variable.
$\cdot^\omega$	Related items of country ω.

I. Introduction

WITH the fast industrial development and global civilization, fossil energy has been overexploited and used, which leads to a series of environmental problems such as air pollution and global warming. Consequently, it poses energy crisis to human beings. To cope with this, China has proposed the global energy interconnection (GEI) concept.

The GEI was originally planned to globally interconnect smart power systems among several countries based on the ultrahigh voltage (UHV) technology in a way to promote the development and utilization of renewable energy sources (RESs) [1]. The key functions of the GEI were presented in [2].

1) *Energy Transaction*: As the carrier of energy transmission, the GEI can transform various kinds of primary energy into electricity that is transmitted to anywhere needed;

2) *Resource Allocation:* Considering time, season, and resource differences among the countries, the GEI can complement the regional disparity of RESs and loads, and thus, balance the load and generation in a wide area.

3) *Information Interaction:* Being the pivot of information interaction, the GEI can collect and analyze massive data to realize a real-time communication among suppliers and consumers.

Hence, the GEI will handle the environmental challenges, lead the sustainable development, and promote the energy revolution.

At present, the GEI has received enthusiastic responses of many regions, including Northeast and Southeast Asia [3], Africa [4], and Arab countries [5], and so on. Meanwhile, the GEI increasingly attracts researchers to study the related issues [6]–[9]. In terms of power systems, one of the most critical issues is the economic dispatch (ED) problem [10], [11]. The ED problem aims to find the optimal generation output with the minimum operation cost over a given number of time periods, while satisfying several operational constraints.

On one hand, RESs usually are uncertain, challenging the power system secure operation in the ED problem. Many methods have been proposed to address this issue, mainly including stochastic methods [12], [13] and robust methods [14]–[23]. The stochastic method gives several representative scenarios with the corresponding probabilities to depict the uncertainty and aims to minimize the expectation of the total cost while satisfying the constraints under selected scenarios. Alternatively, the robust method is to find the optimal solution under the worst case of all possible scenarios in a preset uncertainty set. Compared with the stochastic method, the robust method ensures the feasibility of all possible scenarios, which was more promising in the short-term scheduling. In [14] and [15], an adjustable robust optimization approach was presented, which can optimize the generation at the base point while introducing participation factors to adjust the generation output to ensure sufficient feasibility. To describe the temporal and spatial correlation of uncertainty, dynamic uncertainty sets were introduced in [16]. Moreover, due to the difficulty to capture the exact uncertainty, the distributionally robust optimization (DRO) techniques were discussed in [17]–[19], which defined a distributional set containing all possible probability distributions for the uncertainty. Furthermore, to prevent the conservativeness of robust approaches, the uncertainty budget was used in [20], [21] to make the conventional robust optimization more flexible. In addition, the price of robustness was introduced in [22], [23] to improve the performance of the conventional robust methods.

On the other hand, the information privacy of the power system in each country should be preserved, which prevents the GEI from conducting a centralized optimal dispatch framework. Thus, a distributed algorithm should be considered to protect the confidential information of each country. Various distributed algorithms were studied in the literature. One of the algorithms is the Lagrange relaxation (LR) [24], [25]. The idea of the LR is to allocate the coupling constraints into the objective function by Lagrange multipliers, making the original problem separable. However, the convergence performance is closely related to the choice of parameters and it is practically difficult to design a proper strategy. Accordingly, augmented LR (ALR) methods [26], [27] were proposed, where a quadratic penalty function in the objective function is considered, and thus it improves the convergence performance. Unfortunately, the quadratic penalty function is nonseparable and destroys the decomposition ability of the original problem. To address this, alternating direction method of multipliers (ADMMs) [28]–[30], auxiliary problem principal (APP) [31], [32], and the event-based control framework [33] were further developed. In particular, fully distributed ADMM-based algorithms were proposed in [29] and [30] without the need of a data center to update and allocate the multipliers, rendering a decentralized framework. In addition, besides the above ALR-based distributed algorithms, there are also some other distributed algorithms that can achieve comparable results, for example, neurodynamic-based algorithm [34] and biased min-consensus-based algorithm [35].

Nevertheless, each country has the area control error (ACE) system to manage the difference between scheduled and actual generation under the uncertainties. Due to the practical energy policy in the GEI, the uncertainty of one country should not affect other countries (i.e., net exchanged power in the ACE should be maintained). How to handle the uncertainty and then allocate the corresponding responsibility among countries in the GEI remain unclear. In this article, a zonally robust decentralized ED model is proposed for the GEI and an application to Northeast Asian Countries is studied. The main contributions of this article are listed as follows.

1) A novel zonally adjustable robust ED method is established for the GEI. In this model, a special regulation is specified, in which the uncertainty of RESs in each country should be self-accommodated (i.e., net exchanged power in the ACE should be exactly maintained). In this situation, the tie-line scheduling between countries cannot be changed under any realization of uncertainties once it is given. Thus, the uncertainty in one country cannot affect the power generation output of other countries.
2) The curtailment of RESs is modeled with the consideration of RES uncertainty. In the model, the real RES output interval is decided by the forecasted RES output interval and the RES curtailment limit. Furthermore, to deal with the nonconvexity of the initial curtailment functions, an equivalent linearization approach is used which makes the problem much easier to solve.
3) An ADMM-based decentralized algorithm is adopted for the zonally adjustable robust ED model, leading to a zonally robust decentralized optimization. Only limited information including tie-line power flows and angles at boundary buses can be exchanged between adjacent countries, and the detailed and private information in each country is not required.

The remainder of this article is organized as follows. Section II gives the detailed description of the proposed zonally robust decentralized ED for the GEI and decentralized algorithm. Section III shows a case study on the Northeast Asia countries, and concluding remarks are drawn in Section IV.

II. Proposed Zonally Adjustable Robust ED Model

For a GEI shown in Fig. 1, the countries are connected together by several physical and information tie-lines. The physical tie-lines link the power grid of each country, which can realize the transactive power energy among countries. Meanwhile, the information tie-lines carry and exchange the necessary dispatching information among countries. In each country, there are multienergy resources, including thermal power, wind power, photovoltaic power, and hydropower, which produce electricity to support load demand through internal transmission lines. Note that the thermal power and hydropower can be controlled in a deterministic manner, while the wind power and photovoltaic power will bring uncertainties. In general, a deterministic ED model for the

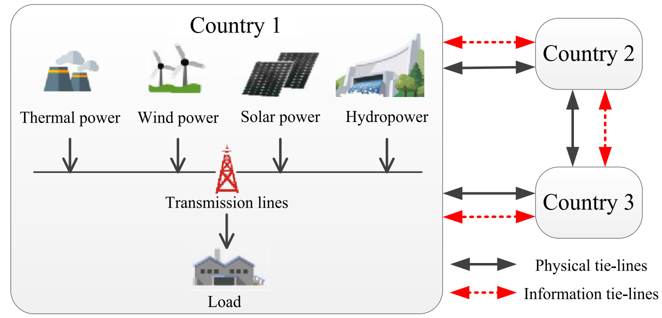

Fig. 1. Economic dispatch diagram of a GEI.

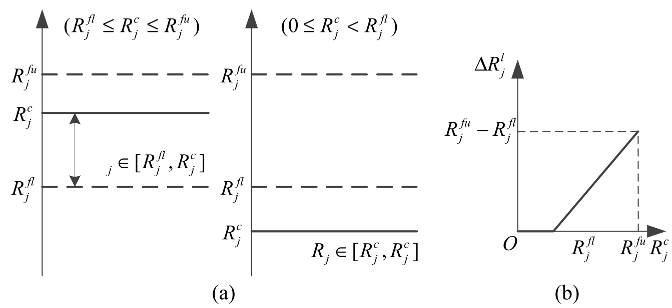

Fig. 2. Impact of the curtailment limit on the RES uncertainty. (a) Real output interval. (b) Uncertainty level.

GEI aims to minimize the total cost over a given number of time periods, while guaranteeing the secure operation constraints and transactive energy contracts of the GEI.

A. Zonally Robust Economic Dispatch Model for the GEI

To address the RES uncertainty, a zonally robust ED model for the GEI is established, in which each country's RES uncertainty is self-accommodated and will not affect the dispatch of other countries.

1) Modeling of the RES Curtailment: Considering the forecasted output of the RES at bus j to be an interval due to the uncertainty, then $R_j^f(t) \in [R_j^{fl}(t),\ R_j^{fu}(t)]$. To guarantee the feasibility of the ED problem, the RES curtailment may happen. Let the curtailment limit of the RES at bus j be $R_j^c(t)$ and the RES output larger than $R_j^c(t)$ will be curtailed. For that, $R_j^c(t)$ has a bound constraint as

$$0 \le R_j^c(t) \le R_j^{fu}(t) \quad \forall t \in \mathbf{T},\ \ j \in \mathbf{\Pi}_R. \tag{1}$$

As shown in Fig. 2(a), when $R_j^{fl}(t) \le R_j^c(t) \le R_j^{fu}(t)$, the RES output is limited within $[R_j^{fl}(t),\ R_j^c(t)]$; when $0 \le R_j^c(t) \le R_j^{fl}(t)$, the RES output is limited within $[R_j^c(t),\ R_j^c(t)]$. Furthermore, as shown in Fig. 2(b), the uncertainty level (i.e., the length of uncertainty interval) $\Delta R_j(t)$ can be expressed as the function of the curtailment limit $R_j^c(t)$ by

$$\Delta R_j(t) = \max\{0, R_j^c(t) - R_j^{fl}(t)\} \quad \forall t \in \mathbf{T}, j \in \mathbf{\Pi}_R. \tag{2}$$

Due to the curtailment limit $R_j^c(t)$, the real RES output interval can be expressed as

$$R_j(t) \in [R_j^c(t) - \Delta R_j(t), R_j^c(t)] \quad \forall t \in \mathbf{T}, j \in \mathbf{\Pi}_R. \tag{3}$$

2) Zonally Robust Economic Dispatch Model: To meet the practical energy policy in the GEI, a zonally robust approach

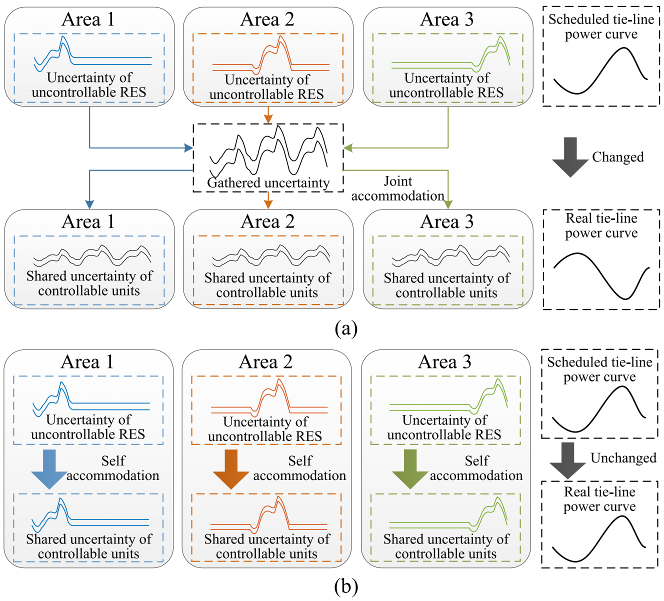

Fig. 3. Traditional and zonally robust model. (a) Traditional adjustable robust model. (b) Zonally adjustable robust model.

in the ED model is designed. To illustrate the zonal robustness, Fig. 3 gives a comparison of the traditional adjustable robust model [14] and the proposed zonally robust model. The traditional robust model gathers all the uncertainty and redistributes them to each country, that id, the total uncertainties are shared. On the contrary, in the proposed model, the tie-line power flows are fixed as the scheduling value under any realization of uncertainty. At that time, one country's uncertainty cannot affect the generation of other countries and the uncertainty is self-accommodate in each country, realizing the zonal robustness.

Based on the above analysis, the zonally adjustable robust ED model for the GEI is given as

$$\min \text{Cost} = \sum_{t\in \mathbf{T}} \left\{ \sum_{i\in \mathbf{\Pi}_G} \left(a_i G_i^0(t) + b_i\right) + \sum_{j\in \mathbf{\Pi}_R} p_R \left(R_j^{fu}(t) - R_j^c(t)\right)^2 \right\} \tag{4a}$$

$$\text{s.t.} \sum_{i\in \mathbf{\Pi}_G} G_i(t) + \sum_{j\in \mathbf{\Pi}_R} R_j(t) - \sum_{d\in \mathbf{\Pi}_D} D_d(t) = 0 \quad \forall t \in \mathbf{T} \tag{4b}$$

$$\underline{G}_i \le G_i(t) \le \bar{G}_i \quad \forall t \in \mathbf{T}, i \in \mathbf{\Pi}_G \tag{4c}$$

$$\underline{\Delta G}_i \le G_i(t) - G_i(t-1) \le \overline{\Delta G}_i \quad \forall t \in \mathbf{T},\ i \in \mathbf{\Pi}_G \tag{4d}$$

$$F_l(t) = \sum_{i\in \mathbf{\Pi}_G} H_{l,i} G_i(t) + \sum_{j\in \mathbf{\Pi}_R} H_{l,j} R_j(t) - \sum_{d\in \mathbf{\Pi}_D} H_{l,d} D_d(t) \quad \forall l \in \mathbf{L}_{in}$$

$$T_l(t) = \sum_{i\in \mathbf{\Pi}_G} H_{l,i} G_i(t) + \sum_{j\in \mathbf{\Pi}_R} H_{l,j} R_j(t) - \sum_{d\in \mathbf{\Pi}_D} H_{l,d} D_d(t) \quad \forall l \in \mathbf{L}_{tl}\ \forall t \in \mathbf{T} \tag{4e}$$

$$-\bar{F}_l \le F_l(t) \le \bar{F}_l \quad \forall l \in \mathbf{L}_{in} \tag{4f}$$

$$-\bar{T}_l \le T_l(t) \le \bar{T}_l \quad \forall l \in \mathbf{L}_{tl} \quad \forall t \in \mathbf{T} \tag{4g}$$

$$\sum_{t\in \mathbf{T}} G_i(t) \le W_i \quad \forall i \in \mathbf{\Pi}_H \tag{4h}$$

$$\sum_{t\in \mathbf{T}} T_l^0(t) = E_l \quad \forall l \in \mathbf{L}_{tl} \tag{4i}$$

$$T_l(t) = T_l^0(t) \quad \forall t \in \mathbf{T} \tag{4j}$$

$$\forall R_j(t) \in [R_j^c(t) - \Delta R_j(t),\ \ R_j^c(t)] \quad \forall t \in \mathbf{T},\ j \in \mathbf{\Pi}_R$$

$$\text{(1) and (2)} \tag{4k}$$

where (4a) is the objective function for minimizing the total costs including the generation cost of thermal units and the curtailment penalty cost of RESs. Constraints (4b)–(4f) are used for power balance, generation limits, units' ramping limits, and transmission line flow limits, respectively. Note that in (4b), the power loss caused by the transmission network is approximately modeled by 7% of the load demand, that is, $D_d(t)$ should be 107% of the initially predicted load demand of bus d at time t. Constraint (4g) describes the limits for hydroelectric energy reserve capacity. Constraint (4h) describes the transactive energy contracts of the tie-lines over the given number of periods. Constraint (4i) fixes the tie-line power flows as the scheduling value under the uncertainty. Constraint (4j) describes the uncertainty interval of RES output and Constraint (4k) restricts the curtailment limit and uncertainty level of RESs.

Notice that the "max" function in (2) is nonconvex, which makes the problem difficult to solve. Fortunately, since the optimization model is to minimize the total cost, a larger uncertainty level will lead to a greater objective value. Thus, the objective function always expects to find the smallest uncertainty level and (2) can be exactly linearized by

$$\Delta R_j(t) \ge 0, \quad \Delta R_j(t) \ge R_j^c(t) - R_j^{fl}(t) \ \forall t \in \mathbf{T},\ \ j \in \mathbf{\Pi}_R. \tag{5}$$

B. Adjustable Robust Method

It can be found that model (4) cannot be directly solved due to the constraint (4j). To handle this, we should eliminate "∀" from the model, which can be realized by the adjustable robust method. The detailed derivation is presented as follows.

First, the generation output of each unit can be adjusted from the base point by the preset participation factor to handle the uncertainty, such that

$$G_i(t) = G_i^0(t) - \sum_{j\in \mathbf{\Pi}_R} \alpha_{ij}(R_j(t) - R_j^c(t)) \quad \forall t \in \mathbf{T},\ i \in \mathbf{\Pi}_G. \tag{6}$$

In the zonally robust model, each country is only responsible for the uncertainties of its own, and thus, the participation factors should satisfy

$$\alpha_{ij} = \begin{cases} \alpha_{ij}^{\omega}, & i, j \in \mathbf{\Pi}^{\omega} \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

Substituting (6) and (7) into (4b) gives

$$\sum_{i\in \mathbf{\Pi}_G} G_i^0(t) + \sum_{j\in \mathbf{\Pi}_R} R_j^c(t) - \sum_{d\in \mathbf{\Pi}_D} D_d(t) = 0 \quad \forall t \in \mathbf{T} \tag{8a}$$

$$\sum_{i\in \mathbf{\Pi}_G^{\omega}} \alpha_{ij}^{\omega} = 1 \quad \forall \omega \in \mathbf{\Omega},\ \ j \in \mathbf{\Pi}_R^{\omega}. \tag{8b}$$

Taking (4e) and (6) and (7) into (4i) gives

$$T_l^0(t) = \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl} \tag{9a}$$

$$\sum_{i\in\mathbf{\Pi}_G^\omega} H_{l,i}^\omega \alpha_{ij}^\omega = H_{l,j}^\omega \quad \forall\omega\in\mathbf{\Omega},\quad l\in\mathbf{L}_{tl},\ \ j\in\mathbf{\Pi}_R^\omega. \tag{9b}$$

For inequality constraints, the adjustable robust method should guarantee the feasibility of the inequality constraints under any realization of the uncertainties. Taking (4f) for example, substituting (4e) and (6) into (4f) gives

$$\begin{aligned} -\bar{T}_l \le & \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{m\in\mathbf{\Pi}_D} H_{l,m}D_m(t) \\ & + (\sum_{i\in\mathbf{\Pi}_G} -H_{l,i}\sum_{j\in\mathbf{\Pi}_R}\alpha_{ij} + \sum_{j\in\mathbf{\Pi}_R} H_{l,j})(R_j(t)-R_j^c(t)) \\ \le & \ \bar{T}_l \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl}. \end{aligned} \tag{10}$$

Define

$$J_l = \sum_{i\in\mathbf{\Pi}_G} -H_{l,i}\sum_{j\in\mathbf{\Pi}_R}\alpha_{ij} + \sum_{j\in\mathbf{\Pi}_R} H_{l,j} \tag{11}$$

$$J_l^+ = \begin{cases} J_l, & J_l>0 \\ 0, & J_l\le 0, \end{cases} \qquad J_l^- = \begin{cases} 0, & J_l>0 \\ J_l, & J_l\le 0. \end{cases} \tag{12}$$

The maximum and minimum power flow limit constraints of (10) under the uncertainty interval (4j) are expressed as

$$\bar{T}_l \ge \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) - J_l^-\Delta R_j(t) \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl} \tag{13a}$$

$$-\bar{T}_l \le \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) - J_l^+\Delta R_j(t) \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl}. \tag{13b}$$

Combining (13a) with (13b), we have

$$J_l^+\Delta R_j^l(t) - \bar{T}_l \le \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) \le J_l^-\Delta R_j(t) + \bar{T}_l \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl}. \tag{14}$$

Furthermore, for $\forall l\in L_{tl}$, taking (9b) into (11) gives $J_l = 0$. Thus, (14) can be simplified as

$$-\bar{T}_l \le \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) \le \bar{T}_l \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl}. \tag{15}$$

Other inequality constraints can be rewritten in the similar way. Define

$$\alpha_{ij}^+ = \begin{cases} \alpha_{ij}, & \alpha_{ij}>0 \\ 0, & \alpha_{ij}\le 0, \end{cases} \qquad \alpha_{ij}^- = \begin{cases} 0, & \alpha_{ij}>0 \\ \alpha_{ij}, & \alpha_{ij}\le 0. \end{cases} \tag{16}$$

The zonally adjustable robust ED for the GEI can be finally reformulated as

$$\min \text{Cost} = \sum_{t\in\mathbf{T}}\left\{\sum_{i\in\mathbf{\Pi}_G}\left(a_iG_i^0(t)+b_i\right) + \sum_{j\in\mathbf{\Pi}_R} p_R\left(R_j^{fu}(t)-R_j^c(t)\right)^2\right\} \tag{17a}$$

$$\text{s.t.} \sum_{i\in\mathbf{\Pi}_G} G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} D_d(t) = 0 \quad \forall t\in\mathbf{T} \tag{17b}$$

$$G_i - \sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^-\Delta R_j(t) \le G_i^0(t) \le \bar{G}_i - \sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^+\Delta R_j(t) \quad \forall t\in\mathbf{T},\ i\in\mathbf{\Pi}_G \tag{17c}$$

$$\begin{aligned} &\Delta G_i + \sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^+\Delta R_j(t-1) - \sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^-\Delta R_j(t) \\ &\le G_i^0(t) - G_i^0(t-1) \\ &\le \overline{\Delta G}_i - \sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^+\Delta R_j(t) + \sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^-\Delta R_j(t-1) \\ &\forall t\in\mathbf{T},\ i\in\mathbf{\Pi}_G \end{aligned} \tag{17d}$$

$$\begin{aligned} &J_l^+\Delta R_j(t) - \bar{F}_l \le \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^0(t) \\ &- \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) \\ &\le J_l^-\Delta R_j(t) + \bar{F}_l \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{in} \end{aligned} \tag{17e}$$

$$T_l^0(t) = \sum_{i\in\mathbf{\Pi}_G} H_{l,i}G_i^0(t) + \sum_{j\in\mathbf{\Pi}_R} H_{l,j}R_j^c(t) - \sum_{d\in\mathbf{\Pi}_D} H_{l,d}D_d(t) \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl} \tag{17f}$$

$$-\bar{T}_l \le T_l^0 \le \bar{T}_l \quad \forall t\in\mathbf{T},\ l\in\mathbf{L}_{tl} \tag{17g}$$

$$\sum_{t\in\mathbf{T}} G_i^0(t) \le W_i - \sum_{t\in\mathbf{T}}\sum_{j\in\mathbf{\Pi}_R}\alpha_{ij}^+\Delta R_j(t) \quad \forall i\in\mathbf{\Pi}_H \tag{17h}$$

$$\sum_{t\in\mathbf{T}} T_l^0(t) = E_l, \quad \forall l\in\mathbf{L}_{tl} \tag{17i}$$

$$\text{(1) and (5).} \tag{17j}$$

In general, the participation factors of units can be deployed by the automatic generation control (AGC) system [14]. Due to the special regulation of the GEI, the preset participation factors should satisfy (7), (8b), and (9b).

III. Decentralized Zonally Adjustable Robust Economic Dispatch Model for GEI

A fully distributed method can be further used to design a decentralized ED model for the GEI, which can be realized by solving independent subproblems for each country, while only exchanging limited information.

A. Branch Splitting Approach

It can be found that the decision variables among multiple countries are coupled by (17b), (17e), and (17g). Moreover, the sensitivity factor is related to the detailed topology information of all the countries in the GEI, and thus, this formulation brings a significant challenge in designing the distributed method directly. To perform the distributed method, the $\boldsymbol{B\theta}$ formulation [36] should be used to conduct the branch splitting approach.

As shown in Fig. 4, for each tie-line mn ($m\in\mathbf{\Pi}^\omega$, $n\in\mathbf{\Pi}^\phi$), the tie-line branch flow T_{mn} is duplicated by T_{mn}^ω and T_{mn}^φ, which represents the power flows from country ω to country

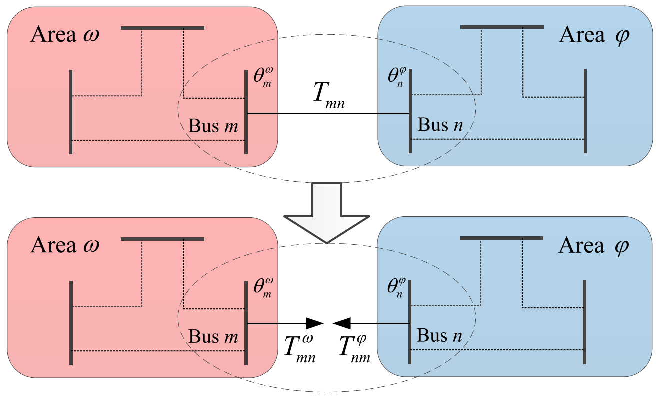

Fig. 4. Process of the branch splitting.

ϕ and from country ϕ to country ω, respectively. By means of the branch splitting approach, constraints (17b), (17e)–(17g), and (17i) can be rewritten as

$$\boldsymbol{B}^{\boldsymbol{\omega}} \cdot \boldsymbol{\theta}^{\boldsymbol{\omega}0}(t) = \boldsymbol{C}_G^\omega \boldsymbol{G}^{\boldsymbol{\omega}0}(t) + \boldsymbol{C}_R^\omega \boldsymbol{R}^{\omega 0}(t) - \boldsymbol{C}_D^\omega \boldsymbol{D}^\omega(t) - \boldsymbol{C}_T^\omega \mathbf{T}^{\omega 0}(t) \quad \forall t \in \mathbf{T},\ \omega \in \boldsymbol{\Omega} \tag{18}$$

$$J_l^+ \Delta R_j(t) - \bar{F}_l \le \sum_{i \in \boldsymbol{\Pi}_G^\omega} H_{l,i} G_i^0(t) + \sum_{j \in \boldsymbol{\Pi}_R^\omega} H_{l,j} R_j^0(t) - \sum_{d \in \boldsymbol{\Pi}_D^\omega} H_{l,d} D_d(t) - \sum_{m \in \boldsymbol{\Pi}_T^\omega, mn \in \mathbf{L}_{tl}^\omega} H_{l,m} T_{mn}(t) \le J_l^- \Delta R_j(t) + \bar{F}_l \quad \forall t \in \mathbf{T},\ l \in \mathbf{L}_{in}^\omega, \omega \in \boldsymbol{\Omega} \tag{19}$$

$$T_{mn}^\omega(t) = -T_{nm}^\varphi(t) = \frac{\theta_m^\omega(t) - \theta_n^\varphi(t)}{x_{mn}(t)} \quad \forall t \in \mathbf{T},\ mn \in \mathbf{L}_{tl},\ (\omega, \varphi) \in \boldsymbol{\Lambda} \tag{20}$$

$$-\bar{T}_{mn}^\omega \le T_{mn}^{\omega 0} \le \bar{T}_{mn}^\omega \quad \forall t \in \mathbf{T},\ mn \in \mathbf{L}_{tl}^\omega,\ \omega \in \boldsymbol{\Omega} \tag{21}$$

$$\sum_{t \in \mathbf{T}} T_{mn}^{\omega 0}(t) = E_{mn}^\omega \quad \forall mn \in \mathbf{L}_{tl}^\omega, \omega \in \boldsymbol{\Omega}. \tag{22}$$

In addition, a reference bus should be set for bus angles of the entire system. Note that the reference bus can be chosen as a certain bus or chosen as a virtual bus, and it gives

$$\theta_{\text{ref}} = 0. \tag{23}$$

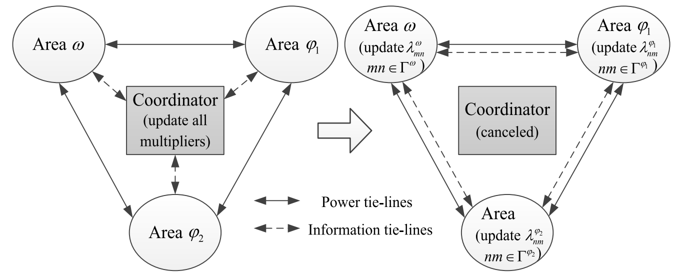

Fig. 5. Modes of the multiplier updating.

Hence, problem (17) is reformulated as

$$\min \text{Cost} = \sum_{t \in \mathbf{T}} \left\{ \sum_{i \in \boldsymbol{\Pi}_G} \left(a_i G_i^0(t) + b_i\right) + \sum_{j \in \boldsymbol{\Pi}_R} p_R \left(R_j^{fu}(t) - R_j^c(t)\right)^2 \right\} \tag{24a}$$

$$\text{s.t. (17c), (17d), (17h), (17i), and (18)} - (23). \tag{24b}$$

B. Decentralized Model

In (24), constraint (20) couples the tie-line variables between the adjacent countries, which will be relaxed to realize the distributed method using the ALR, leading the objective function (24a) to be (25), as shown at the bottom of this page, where $\lambda_{mn}^\omega(t)$ and $\lambda_{mn}^\varphi(t)$ are the Lagrange multipliers corresponding to (20) and ρ is the positive penalty coefficient.

However, the quadratic penalty terms in (25) destroy the decomposition ability of the optimization problem, which can be resolved by the ADMM. When solving the optimization problem of one country, the variables of other countries are fixed as the latest results. Moreover, as shown in Fig. 5, the multipliers' updating process does not need a coordinator, but it can be allocated to each country and form a fully distributed framework. Specifically, country ω is responsible for updating λ_{mn}^ω ($mn \in \mathbf{L}_{tl}^\omega$). Using the ADMM, the subproblem of country ω in the $(k+1)$th iteration is formed as (26), shown at the bottom of this page, where $U_\varphi^{\omega(k+1)}$ and $V_{mn}^{\omega(k+1)}(t)$

$$L = \text{Cost} + \sum_{t \in \mathbf{T}, mn \in \mathbf{L}_{tl}, (\omega,\varphi) \in \boldsymbol{\Lambda}} \left\{ \left[\lambda_{mn}^\omega(t) \left(T_{mn}^\omega(t) - \frac{\theta_m^\omega(t) - \theta_n^\varphi(t)}{x_{mn}} \right) + \frac{\rho}{2} \left(T_{mn}^\omega(t) - \frac{\theta_m^\omega(t) - \theta_n^\varphi(t)}{x_{mn}} \right)^2 \right] + \left[\lambda_{nm}^\varphi(t) \left(-T_{nm}^\varphi(t) - \frac{\theta_m^\omega(t) - \theta_n^\varphi(t)}{x_{mn}} \right) + \frac{\rho}{2} \left(-T_{nm}^\varphi(t) - \frac{\theta_m^\omega(t) - \theta_n^\varphi(t)}{x_{mn}} \right)^2 \right] \right\} \tag{25}$$

$$\min L_{\text{ADMM}}^{\omega(k+1)} = \text{Cost}^\omega + \sum_{\substack{t \in \mathbf{T}, mn \in \boldsymbol{\Gamma} \\ (\omega,\varphi) \in \boldsymbol{\Lambda}}} \left\{ \left[\lambda_{mn}^{\omega(k)}(t) \left(T_{mn}^\omega(t) - \frac{V_{mn}^{\omega(k+1)}(t)}{x_{mn}} \right) + \frac{\rho}{2} \left(T_{mn}^\omega(t) - \frac{V_{mn}^{\omega(k+1)}(t)}{x_{mn}} \right)^2 \right] - \left[\lambda_{nm}^{\varphi(k)}(t) \left(U_\varphi^{\omega(k+1)}(t) + \frac{V_{mn}^{\omega(k+1)}(t)}{x_{mn}} \right) - \frac{\rho}{2} \left(U_\varphi^{\omega(k+1)}(t) + \frac{V_{mn}^{\omega(k+1)}(t)}{x_{mn}} \right)^2 \right] \right\} \tag{26a}$$

$$\text{s.t. (17c), (17d), (17h), (17i), (18), (19), and (21)} - (23), \text{ for } \omega \tag{26b}$$

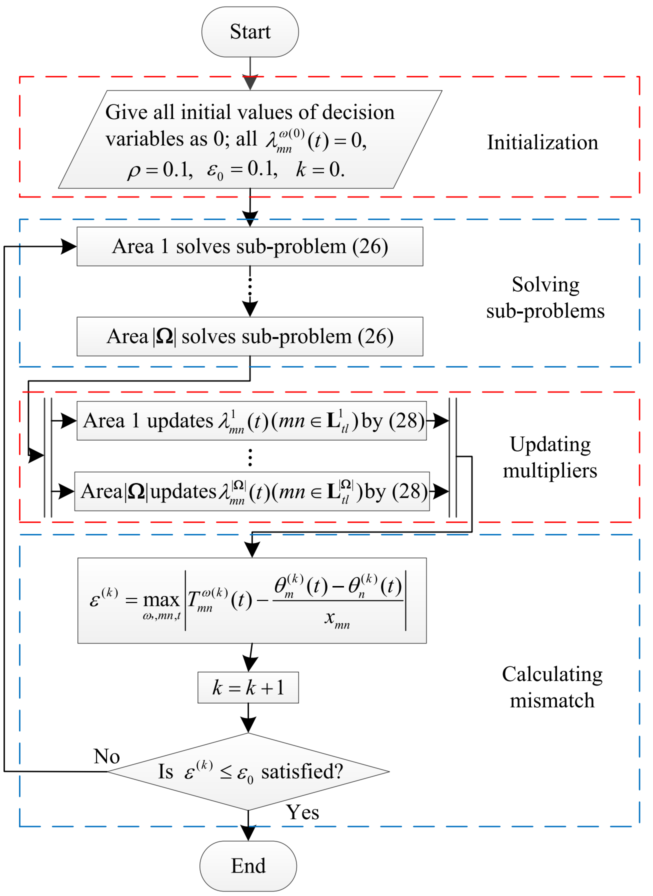

Fig. 6. Flowchart of the decentralized zonally adjustable robust economic dispatch model for the GEI.

represent the latest $T_{mn}^{\varphi}(t)$ and $\theta_m(t)-\theta_n(t)$ for country ω in the $(k+1)$th iteration, respectively, which are given as

$$U_{\varphi}^{\omega(k+1)}(t)=\begin{cases}T_{nm}^{\varphi(k+1)}(t), & \omega>\varphi\\ T_{nm}^{\varphi(k)}(t), & \omega<\varphi\end{cases}$$
$$V_{mn}^{\omega(k+1)}(t)=\begin{cases}\theta_m^{\omega}(t)-\theta_n^{\varphi(k+1)}(t), & \omega>\varphi\\ \theta_m^{\omega}(t)-\theta_n^{\varphi(k)}(t), & \omega<\varphi\end{cases}$$
$$\forall t\in\mathbf{T},\ mn\in\mathbf{L}_{tl}^{\omega},\ (\omega,\varphi)\in\mathbf{\Lambda}. \quad (27)$$

The multipliers are updated by (28) in the $(k+1)$th iteration as

$$\lambda_{mn}^{\omega(k+1)}(t)=\lambda_{mn}^{\omega(k)}(t)+\rho\left(T_{mn}^{\omega(k+1)}(t)-\frac{\theta_m^{\omega(k+1)}(t)-\theta_n^{\varphi(k+1)}(t)}{x_{mn}}\right)$$
$$\lambda_{nm}^{\varphi(k+1)}(t)=\lambda_{nm}^{\varphi(k)}(t)+\rho\left(-T_{nm}^{\varphi(k+1)}(t)-\frac{\theta_m^{\omega(k+1)}(t)-\theta_n^{\varphi(k+1)}(t)}{x_{mn}}\right)$$
$$\forall t\in\mathbf{T},\ mn\in\mathbf{L}_{tl},\ (\omega,\varphi)\in\mathbf{\Lambda}. \quad (28)$$

Finally, the flowchart of the proposed decentralized zonally adjustable robust ED model for the GEI is shown in Fig. 6, which consists of four parts: initialization, solving subproblems, updating multipliers, and calculating mismatch. Here, ε represents the maximum mismatch of the relaxed constraints and ε_0 is the tolerance of the mismatch.

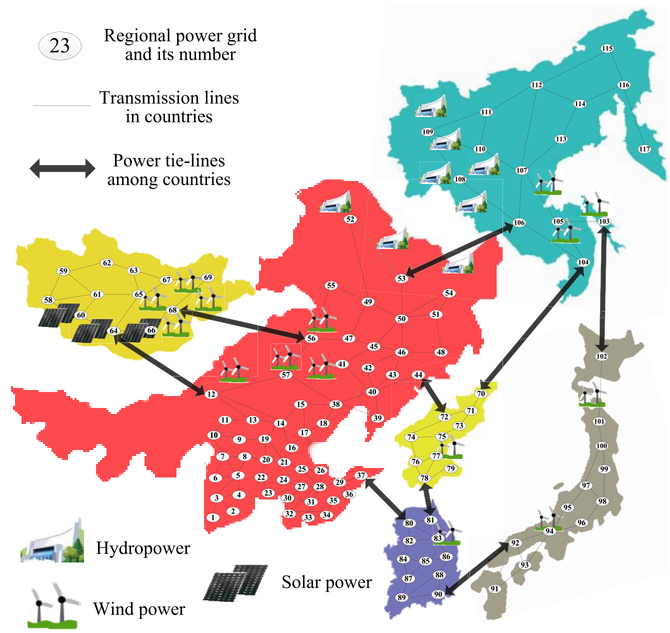

Fig. 7. Simulation case of the Northeast Asian transnational interconnection.

TABLE I
RES ENERGY MIX OF THE NORTHEAST ASIA COUNTRIES

Countries	RESs	# of Bases	Total Capacity/GW
NNC	Hydropower	---	14.5
	Wind power	5	135
Mongolia	Wind power	5	81.9
	Solar Power	5	505
Japan	Wind power	2	25.5
North and South Korea	Wind power	2	34.5
RFE	Hydropower	---	40
	Wind power	5	150

IV. CASE STUDY

In this section, Northeast Asia transnational power systems are chosen as an example of the intracontinental GEI, including six countries/regions: North and Northeast China (NNC), Mongolia, North Korea, South Korea, Japan, and the Russian Far East (RFE). Due to the geographical features, the distribution of RESs in the Northeast Asia is uneven and several RES bases are described as follows: The West RFE and Northeast China contain large water source bases; the South RFE, East Mongolia, and NNC are abundant in wind sources, and South Mongolia has solar resource bases. The topology and the energy distribution of RESs are shown in Fig. 7, and the energy mix is shown in Table I. Moreover, Fig. 8 provides the typical curves of load demand, wind power, and photovoltaic power with uncertainties.

Fig. 9 shows the dispatch results of the separated and interconnected modes in the GEI. In the separated mode, the thermal power accounts for a large proportion in the countries, especially in NNC, North Korea, South Korea, and Japan. More than 50% power energy of RESs over 24 h is curtailed and the RES generation accounts for 25% of the

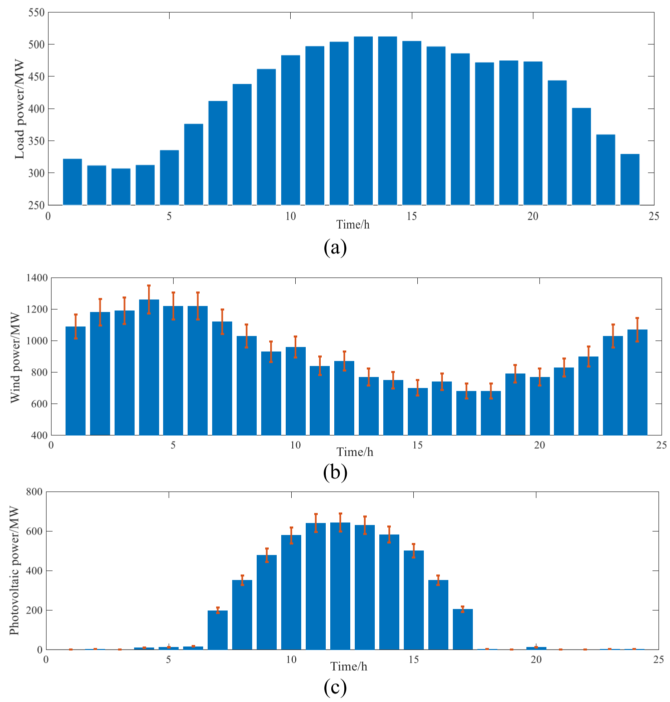

Fig. 8. Typical curves of load demand, wind power, and photovoltaic power. (a) Load power curve. (b) Wind power curve. (c) Photovoltaic power curve.

TABLE II

UNIT OUTPUTS AND LINE POWER FLOWS OF THE PROPOSED MODEL UNDER DIFFERENT SCENARIOS

Scenarios	G_{10} (10) /GW	$F_{10\text{-}11}$(10) /GW	G_{80} (10) /GW	$F_{92\text{-}93}$(10) /GW	$T_{56\text{-}68}$(10) /GW
1	16.0586	-3.1926	20.1527	18.5246	-14.3579
2	16.3022	-3.4525	20.1527	18.5246	-14.3579
3	16.5458	-3.7124	20.1527	18.5246	-14.3579
4	16.7894	-3.9723	20.1527	18.5246	-14.3579
5	17.0330	-4.2322	20.1527	18.5246	-14.3579

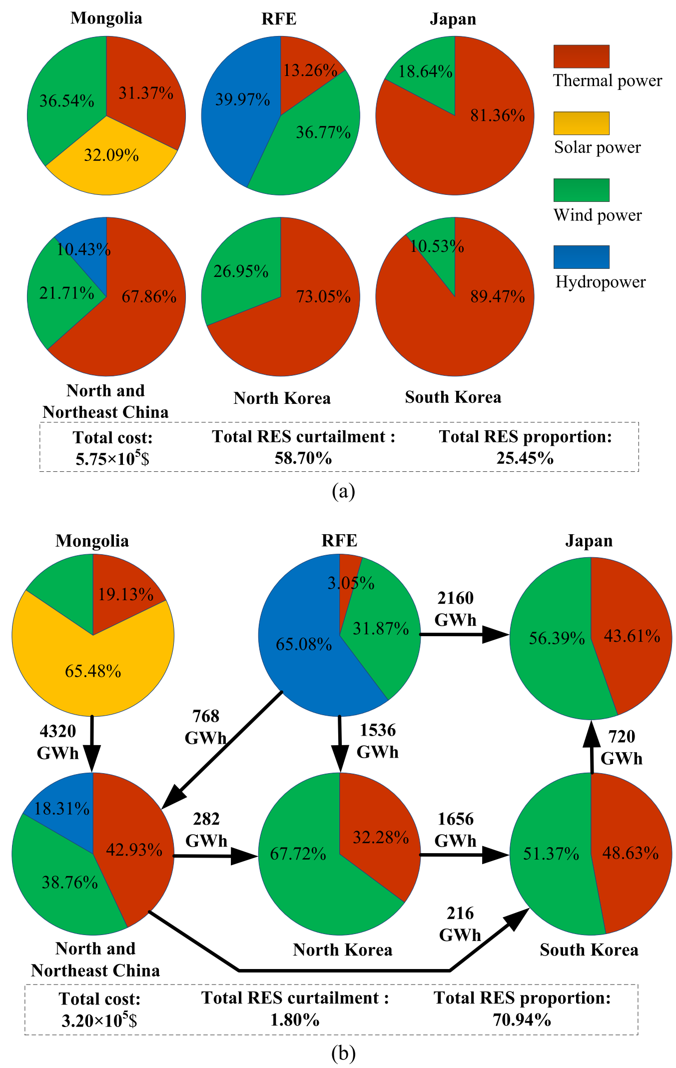

Fig. 9. Dispatching results of the separated and interconnected modes. (a) Separated mode. (b) Interconnected mode.

total energy mix. In contrast, the interconnected mode can significantly reduce the proportion of thermal power in each country and promote the accommodation of RESs. The total RES curtailment is only 1.80% and the proportion of RES generation reaches to 70%. In addition, the total cost of the interconnected mode is less than 60% of the separated mode. Thus, the GEI can accommodate more RESs and lead to less operation cost.

Furthermore, the zonal robustness of the proposed model under five given realizations of the RES output (defined as "scenarios") is analyzed in Table II. Among these five scenarios, it is considered that the realizations of the RES in the NNC are different, while the RES output realizations in other countries are identical. For each given scenario, the unit outputs and line power flows by the proposed model can be calculated, as shown in Table II. For different scenarios, the unit outputs and power flows on the interior transmission line of the NNC are volatile, but the unit outputs and power flows of other countries are unchanged. Moreover, it can be found that the tie-line power flows are strictly kept the same as the scheduled value under any scenarios. This suggests that the uncertain RES output in one country will not affect the dispatch of other countries and the transactive power on the tie-lines, verifying the zonal robustness of the proposed model. In contrast, Table III gives the unit outputs and line power flows obtained by the traditional robust model [shown in Fig. 3(a)]. In Table III, the scenarios are set the same as those in Table II. It is clear that for different scenarios, the unit outputs and power flows of the NNC and other countries are all changed, and the tie-line power flows are also different, failing to be kept the same as the scheduled value. This demonstrates that the traditional robust model does not have the characteristic of zonal robustness, which is not appropriate to be used in the GEI.

Moreover, Table IV compares the results obtained from the centralized and decentralized methods using the same zonally robust ED model. Here, the centralized method is considered as the benchmark. Compared with the benchmark, the decentralized method can provide highly accurate results, with relative errors of decision variables less than 2% and relative error of objective values only 0.01%. In addition, the maximum mismatch of the relaxed constraints and the objective value

TABLE III
UNIT OUTPUTS AND LINE POWER FLOWS OF TRADITIONAL ROBUST MODEL UNDER DIFFERENT SCENARIOS

Scenarios	G_{10}(10) /GW	$F_{10\text{-}11}$(10) /GW	G_{80}(10) /GW	$F_{92\text{-}93}$(10) /GW	$T_{56\text{-}68}$(10) /GW
1	15.0139	-2.0767	21.7867	18.5656	-17.8204
2	15.3295	-2.4013	22.0716	19.3398	-17.1361
3	15.6451	-2.7258	22.3565	20.1139	-16.4519
4	15.9607	-3.0503	22.6414	20.8880	-15.7677
5	16.2763	-3.3749	22.9263	21.6622	-15.0834

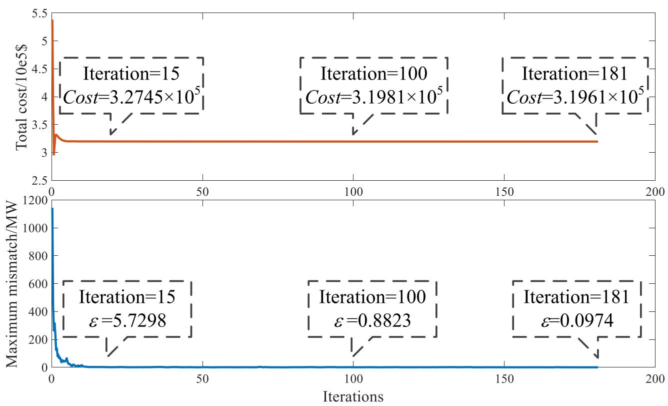

Fig. 10. Iteration process of the decentralized method.

TABLE IV
COMPARISON OF CENTRALIZED AND DECENTRALIZED METHODS

Method	G_{10}(10) /GW	$F_{10\text{-}11}$(10) /GW	$T_{56\text{-}68}$(10) /GW	$Cost/10^5$\$
Centralized	16.0608	-3.1926	-14.3579	3.1958
Decentralized	16.1016	-3.2292	-14.1068	3.1961
Relative error	0.25%	1.15%	1.75%	0.01%

during the iteration process are shown in Fig. 10. Along with the iteration process, the maximum mismatch is decreasing and the objective value is approaching the optimum. At the beginning of the iteration process, the maximum mismatch decays rapidly and the mismatch is 5.7298 in the 15th iteration. Furthermore, the mismatch arrives at 0.8823 in the 100th iteration, where the objective value is close to the optimum. The iteration process stops after 181 iterations, which satisfies the criterion $\varepsilon < 0.1$. In conclusion, the decentralized methods of the zonally robust ED problem can obtain precise results with acceptable iterations.

V. CONCLUSION

In this article, a decentralized zonally adjustable robust ED model was proposed for the GEI. Case studies have indicated that the GEI can effectively promote the accommodation of RES and increase the RES proportion of power generation. Furthermore, the dispatching results from various scenarios verified the zonal robustness of the proposed model, which can guarantee the tie-line power remaining the same as the scheduled value under any realization of uncertainty. Thus, the RES power fluctuation in one country will not affect other countries. In addition, by comparing with the centralized mode, it can be concluded that the decentralized method of the zonally robust ED problem can obtain accurate results through iterations, which protect the information privacy of the GEI's countries.

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